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Modern Interferometers
C. Candler, Hilger + Watts
1951

CHAPTER XVII.

CONCAVE GRATINGS. METHODS OF MOUNTING.

1. Historical. The concave grating was described by Rowland in 1882; the theory has been much simplified by later writers, but all the essential points were clearly stated by Rowland himself in two papers published within the year (1882, 1883; Ames, 1889). Thus he showed that object and image must lie on the arc of a circle, which is drawn on the principal radius of the grating as diameter; that the concave grating is astigmatic, a point source producing a line image; that if the plate is placed facing the grating and on the opposite side of the circle, the spectrum will be normal, the displacement of the line being proportional to the wavelength. He also pointed out that the orders overlap and that this property may be used to measure wavelengths in the infra-red and ultra-violet, for the focal curve is the same for all wavelengths, so that an adjustment made in the visible is valid in the infra-red. Rowland understood too, as some of his critics did not (Glazebrook, 1883), that the rulings must be equally spaced along a chord and not along an arc.

The theory of the grating, thus formulated by Rowland, was elaborated in the next two decades by Runge and Kayser (1901). Kayser's treatment is mathematically complete, but formally somewhat laborious. Since that time the argument has been clarified and simplified in books by Wood (1934) and Meyer (1934).

The early mounts, designed by Rowland himself and by Paschen, aimed at accurate measurement of wavelength; that they require a large room, which can be blacked-out and kept at a uniform temperature, mattered little, so long as the grating remained an academic instrument. In the last two decades, however, the grating has begun to compete with the quartz prism in industrial spectrochemical analysis, especially in the United States; and for this the old mounts have been largely replaced, either by a Littrow type designed by Eagle (1910), or by a stigmatic mount due to Wadsworth (1895).

2. Prism and grating compared. When wavelengths have to be measured as accurately as possible, everyone recognises that a grating is much preferable to a prism. If the Rowland mount is used, the spectrum is normal, and the dispersion can easily be made very high by using the third or fourth order; space and long exposure are difficulties which can be overcome, while astigmatism is of no account.

Use the spectrograph for spectrochemical analysis, however, and the position is quite different; high dispersion is still important, but a normal spectrum is of little account since wavelengths are easily determined by interpolation between two lines of the iron arc; while, when the analysis is to be quantitative, a stigmatic image is almost essential. When these desiderata are considered in detail, the grating is seen as comparable with the prism spectrograph, but not necessarily its superior.

The greater the dispersion of a spectrograph the easier it is to separate two lines lying close to one another, and therefore the easier to distinguish an element with certainty. This is of great importance when working with elements like iron, chromium, and the rare earths which have very complex spectra; on the other hand high dispersion is not necessary for work on the non-ferrous alloys. Thus, in practice, a medium quartz spectrograph, which takes the whole spectrum from 2000 A to 8000 A on one plate is commonly used for work on the non-ferrous alloys, and a large quartz spectrograph using three plates to cover the same range for ferrous alloys.

Slavin (1940) has compared a grating of 3 metre focal length set in an Eagle mount with a large quartz spectrograph, and has shown that the grating has the higher dispersion for all wavelengths greater than 2500 A, even when the first order is used; while if the second order is used, the grating has the higher dispersion above 2150 A. This comparison is not, however, quite fair, for many quartz spectrographs are made with an interchangeable glass train, and this has a much higher dispersion than quartz above 4000 A; moreover the focal length of a large spectrograph is nearer $1\frac{1}{2}$ than 3 metres.

Astigmatism is of little account in qualitative analysis, though even here it prevents the use of the Hartmann diaphragm to produce adjacent spectra, and a mechanical diaphragm placed in front of the plate is open to criticism. But in modern methods of quantitative analysis a stigmatic spectrum is almost essential, for all methods thus far invented for working with an astigmatic image are open to serious objection.

A stigmatic image is formed both by a prism and by a grating in a Wadsworth mount; but the Eagle mount, which in other ways is more convenient than the Wadsworth, produces an astigmatic spectrum, and methods of correcting this are at best inconvenient and cumbersome.

The grating has migrated from the university to industry only within the last decade, so few instrument-making firms have given it the attention, which they have lavished on the quartz spectrograph; even to-day a fully automatic spectrograph is usually found to employ a prism rather than a grating. A quartz spectrograph can be ordered from any one of a number of optical firms. An original grating on the other hand can be

obtained only from one of the half-a-dozen laboratories which rule them, and for this one may have to wait years, and even then obtain it only because one is able to interest someone, who controls their disposal. Concave grating replicas seldom, if ever, achieve the high optical standard required. On the other hand there seems no reason why many more ruling machines should not be built, if there is a steady demand, while the supply of good optical quartz is all too probably limited. Already, indeed, report suggests that more than one optical firm is in difficulties with its supply, and is having to use quartz of a quality, which it would have thrown on the scrap heap not many years ago.

The speed of a grating ruled on speculum metal is much slower than that of a prism, but gratings ruled to throw much of the energy into a particular order and using an aluminised surface are as fast as a prism (Slavin, 1940; Wood, 1944). In spectrochemical analysis this is a matter of no little importance, for the exposure must often be kept short.

In comparing speeds, the intensity lost through astigmatism must not be forgotten; while when two orders overlap, a colour filter is usually necessary to remove the one not wanted, and as no filter is perfect, this further lengthens the exposure. Against this one may set the light scattered by a prism, for in a Littrow mount especially a prism usually scatters more light than a grating, since there are many more surfaces. In a grating, scattered light derives chiefly from scratches on the surface and one may hope that this will be largely eliminated, when gratings can be ruled on some backing and covered with a film of aluminium, the latter being replaced whenever it is scratched or tarnished (Harrison, 1940).

3. Theory of the Rowland circle. The proof of the Rowland circle commonly given follows the treatment of Runge (1895). This is complete mathematically, but does not make the physical principles involved as clear as the treatment adopted by Meyer (1934) many years later. Both base their arguments on the interference condition, though this obscures the close connection between the Rowland circle and the condition for the vertical focal line of a concave mirror. An argument deriving from the law of the extreme path avoids this objection. *

* Beutler (1945) derived the whole theory of the concave grating, including the Rowland circle and the Wadsworth mount, from Fermat's principle of least time. An ingenious, though essentially simple, series development enables him to obtain expressions for the astigmatism, horizontal focus, largest useful aperture and curvature of the image. That his treatment is both more thorough and more direct than that given below, there can be no doubt, and it is likely to be adopted as standard by all future writers. But unfortunately Beutler's paper did not come to the author's notice until the manuscript of the present work was in the publisher's hands, and a complete recasting of the argument seemed likely to cause confusion.

Take the argument from interference first, and consider a bundle of rays passing through a slit O and forming an image at O′, after being diffracted by the grating (Fig. 17.1). The condition that rays from successive rulings shall reinforce one another is

$$b(\sin I+\sin I')=m\lambda \qquad (17.1)$$

where b is the grating space, I and I' the angles of incidence and diffraction, and m the order of the spectrum. This condition must hold not only at

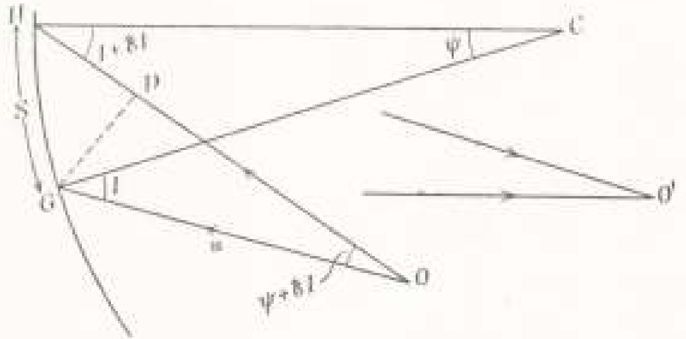

Fig. 17.1.—Theory of the Rowland circle. Monochromatic rays from the source *O* strike the grating *GH* whose centre of curvature is *C* and form an image *O′*.

the G, centre of the grating surface, but for any other point, such as H, on the surface of the grating; in other words the equation must hold when small changes δI and $\delta I'$ occur in values of I and I' while b, m, and λ remain constant. Differentiation shows that this will be true only when

$$\cos I\ \delta I+\cos I'\ \delta I'=0. \qquad (17.2)$$

This fundamental equation may be obtained without any mention of equal ruling spaces, if one may assume a surface which scatters light in planes perpendicular to the rulings. The law of the extreme path (Meyer, 1934) states that the path from object to image must be constant, when the point at which the light is scattered moves a short distance across the surface. Fig. 17.1 shows that the path of a ray diffracted at a point H, distant s from the pole of the surface, is of length

$$u+s\ \sin(I+\delta I)+u'+s\ \sin(I'+\delta I') \qquad (17.3)$$

where u and u' are, respectively, the object and image distance at the pole. This will be constant for a small change in s only if

$$\sin(I+\delta I)+\sin(I'+\delta I')=0$$

a condition which may be re-written in the form already obtained in equation (17.2),

$$\cos I\ \delta I+\cos I'\ \delta I'=0.$$

This derivation shows that the relationship for the vertical focal line of a concave grating must be valid for a concave mirror as well; though in a mirror the condition that in specular reflection $I+I'=0$ must be added. The simplest solution of the differential equation (17.2) is

$$\delta I=\delta I'=0 \qquad (17.4)$$

which is equivalent to

$$\angle HOG=\angle HO'G=\angle HCG \qquad (17.5)$$

so that O and O′ are cyclic with H, G, and C; or O and O′ lie on a circle drawn with GC as diameter. This circle is known as the Rowland circle. The grating surface lies outside the Rowland circle, except at the pole where the two spheres have a common tangent.

The general solution is more complex. In Fig. 17.1, GD, a perpendicular from G on OH, is of length

$$s\ \cos(I+\delta I)=u\ \sin\ (\psi+\delta I) \qquad (17.6)$$

or approximately

$$s\ \cos I=u\ \sin\left(\frac{s}{R}+\delta I\right) \qquad (17.7)$$

so that

$$\delta I=\frac{s\cos I}{u}-\frac{s}{R}. \qquad (17.8)$$

A similar argument applied to the image shows that

$$\delta I'=\frac{s\cos I'}{u_V}-\frac{s}{R} \qquad (17.9)$$

where the suffix V is added to the image distance u', to emphasise that the distance to the vertical focal line is the quantity measured. Substituting these values in equation (17.2), we obtain

$$\frac{\cos^2 I}{u}+\frac{\cos^2 I'}{u_V}=\frac{\cos I+\cos I'}{R} \qquad (17.10)$$

This general equation has many applications. If the reflection is specular, $I+I'=0$, and it reduces to the usual equation for the vertical focal line of a concave mirror

$$\frac{1}{u}+\frac{1}{u_V}=\frac{1}{R\cos I}. \qquad (17.11)$$

Applied to a grating, a simple algebraic transformation converts it into the form which is commonly quoted

$$u_V=\frac{Ru\cos^2 I'}{u(\cos I+\cos I')-R\cos^2 I}. \qquad (17.12)$$

The Rowland circle in which

$$u = R \cos I \qquad (17.13)$$

$$u'_V = R \cos I' \qquad (17.14)$$

is but one example of the general solution, one example but practically far the most important. Indeed the only other solution which appears to be used at all is the Wadsworth mount, in which parallel light is incident on a grating rotated so that it always faces the plate; in symbols this reads $I' = 0$ while $u \rightarrow \infty$,

giving

$$u_V = \frac{R}{1 + \cos I} \qquad (17.15)$$

which is the polar equation of a parabola.

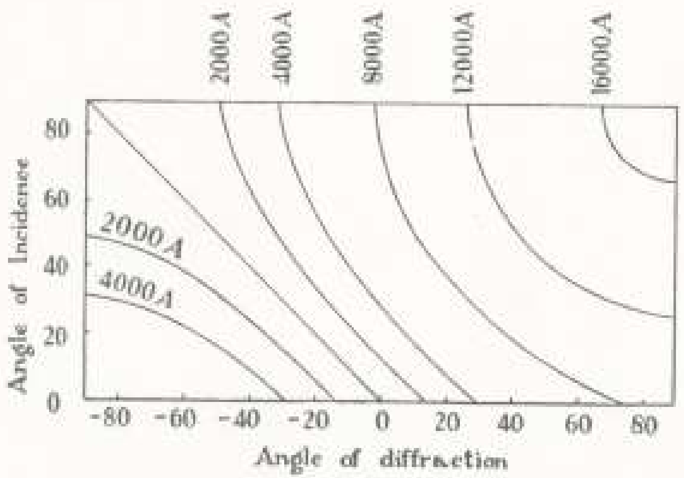

FIG. 17.2A.—The wavelengths appearing in the first order of a grating ruled with 30,000 lines per inch for all angles of incidence and diffraction. (Beutler, 1945.)

Whether the spectral lines, which appear in the positions determined by these mirror equations, are sharp or diffuse, depends on how closely the grating satisfies the interference condition $b(\sin I + \sin I') = m\lambda$. This is a question which will be discussed when the aberration of a concave grating is considered.

4. Five mounts for the visible and near ultra-violet. Some mechanical system must be devised which will keep slit, grating, and plate on the Rowland circle; many have been proposed (Baird, 1939), but only five have been widely used.

In the days when gratings were employed as a primary method of measuring wavelength, the Rowland mount, which gives a normal spectrum, and the Paschen mount, which is very rigid and can be left in permanent adjustment, were popular; but both require so much space that they can be used only in a large basement room, specially devoted to their use.

For spectrochemical analysis the Eagle, Wadsworth, and Abney mounts have been adopted by different instrument makers. The chief desiderata are astigmatism and convenience. The Wadsworth mount is astigmatic, and the Abney permits correction over a wide range of wavelengths; the astigmatism of the Eagle is as small as any Rowland circle mount, and if the mount is modified by placing the source at the side of the plate, it may be corrected over a range, which is wide enough for most analyses.

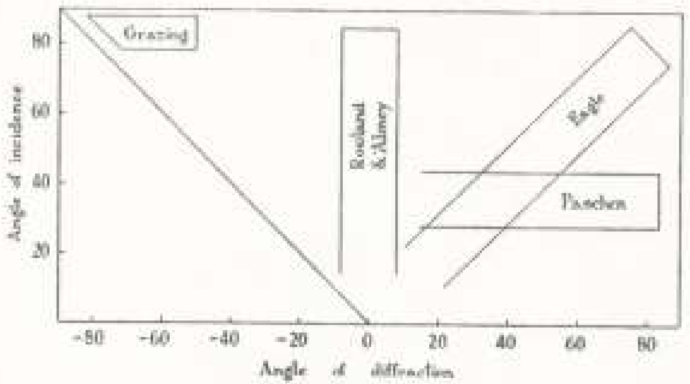

FIG. 17.2B.—The range of angles covered by the various mountings of a concave grating. (Beutler, 1945.)

In convenience the Eagle mount comes easily first; it is the only mount, which can be made so compact that it can be moved from one part of a laboratory to another like a quartz spectrograph, at least in the larger sizes. To change the range in the Abney the source must be moved, while in the Wadsworth the source and plateholder are situated at opposite ends of the instrument. For these reasons some authorities (Dieke, 1939; Harrison, 1940) have even gone so far as to advocate the Eagle mount for all purposes.

Once the ruling space has been chosen the wavelength for given angles of incidence and diffraction is determined by the interference condition, and can be shown graphically (Fig. 17.2A). The type of mount limits the possible angles of incidence and diffraction to the ranges shown in fig. (17.2B). In using these figures a wavelength of

4000 A in the second order is to be read as 8000 A in the first order, and a correction for change in ruling space is equally easy to make.

5. Eagle mount. The Eagle (1910) mount for a concave grating resembles the Littrow mount for a prism, the plate being placed near the slit so that the angle of reflection is nearly equal to the angle of incidence.

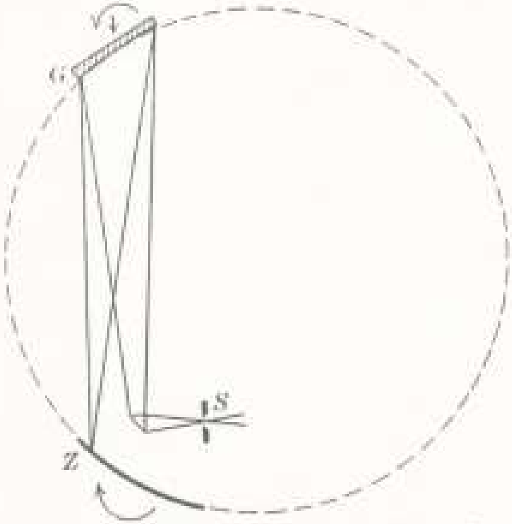

Fig. 17.3A.—Eagle mount with a reflecting prism above the centre of the plate. The arrows show the motions required to move to longer wavelengths.

In the original Eagle mount the source was placed off the axis of the instrument, and a right-angled prism mounted just above the plate (Fig. 17.3A), but to-day the slit is more commonly placed close to the edge of the plate and on the same level (Fig. 17.3B). In the ultra-violet the astigmatism is smaller, when the slit is on the short wavelength side of the plate than when it is on the long wavelength side; but in the latter position the astigmatism changes more slowly with wavelength, so that it may be better corrected over a range of say 1000 A.

The Littrow principle makes the Eagle mount much more compact than any of the alternatives; when the grating is of large radius this is a very great advantage, for the instrument can be neatly housed under a cover and used in a lighted room, whereas most other mounts must be used in rooms from which all light is excluded. Further, the mount is so rigid that vibration shakes the instrument as a whole and does not impair definition.

In industrial instruments of short focal length change of temperature is seldom of any account; for one thing the exposures are short, and for

another the grating is mounted on a cast-iron base, and the coefficients of expansion of glass and cast-iron are so close, that expansion of the instrument as a whole does not affect definition. In academic work, however, a grating of 21-foot radius may be required to reveal weak lines, which require an exposure of twelve hours or more; and here the

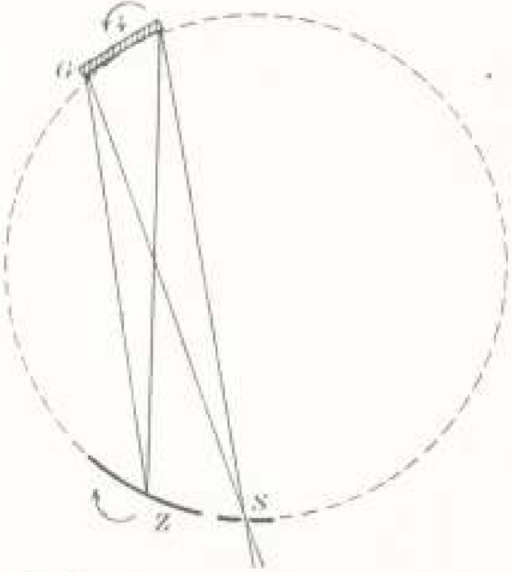

Fig. 17.3B.—Modified Eagle mount with the entrance slit at one edge of the plate.

Eagle mount shows up very favourably, for if the box which houses it is lagged with $1\frac{1}{2}$ inches of wool slag, temperature change can be made so slow, that the instrument contracts and expands as a whole. Neither a Paschen nor Rowland mount can be conveniently lagged, and both must therefore be used in a room, whose temperature can be held constant to $\frac{1}{2}$° C.

A simple calculation shows that even a small change of temperature will make lines appreciably less sharp. The wavelength λ is proportional to the grating space b, so that $\delta\lambda/\lambda = \delta b/b$, and $\delta b/b$ is about 2.10^{-5} for a temperature change of 1° C. This means that in the region of 5000 A the wavelength will change by 0.1 A. Now a 4-inch grating ruled with 15,000 lines per inch will resolve lines 0.08 A apart, so that a change of temperature of 1° C. during an exposure will make it impossible to resolve lines nearer than 0.18 A. Moreover, if lines creep during an exposure, accurate comparison with a superposed spectrum is impossible.

True, the spectrum obtained with an Eagle mount is not normal, but the dispersion will seldom change by more than 2 per cent. on a strip of film 25 cm. long, so that linear interpolation over a distance of 1 cm. will seldom produce appreciable error. When the highest accuracy is required, an error curve ought to be drawn, showing the difference between the true wavelength of an intermediate standard and the wavelength of the same line calculated by linear interpolation between two standards. This precaution is necessary whatever the mounting.

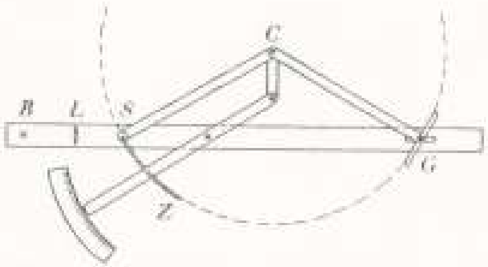

FIG. 17.4.—System of levers used in the Eagle mount, showing how all movements are controlled by a single arm moving over a scale. (Dowell, 1940.)

When moving from one region of the spectrum to another, three settings have to be changed, the angle of the plate, the angle of the grating, and the distance between the two. One system sets the controls to points determined by a calibration curve (Baird, 1939); a better technique uses a system of levers designed to control all three settings by moving a single handle.

The mechanism adopted by Dowell (1940) consists of two levers, each of length equal to half the radius of the grating, joined together at C (Fig. 17.4). The entrance slit S is fixed and one lever SC pivots about a point immediately beneath it; the plate-holder Z also pivots about S, its motion being controlled by the lever SC, to which it is rigidly attached; the grating G is free to move along a slot cut in the base of the instrument, the line of the slot passing through S; at the same time the grating rotates on a roller mount, whose axis lies in the plane of the grating; both motions are controlled by the second lever GC. This mechanism ensures that both plate and grating always lie on the Rowland circle; it is adjusted by a third lever, which moves over a scale calibrated to read the wavelength range in the first order.

The objection most frequently urged against the Eagle mount is that it is not stigmatic (Harrison, 1940), and there was a time when this objection was well-founded. In recent years, however, methods have been devised which will make the grating almost stigmatic over a range of say 1500 Å, and this more than covers the range used in the spectrographic analysis of industrial alloys. The methods of correction are fully discussed in a later section. At a given wavelength, the astigmatism in the Eagle mount is smaller than in the Rowland or Abney.

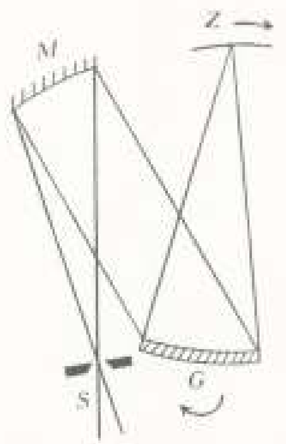

Fig. 17.5.—Wadsworth mount. The entrance slit is in the focal plane of the mirror *M* so that a parallel beam falls on the grating; the plate *Z* is placed at the centre of curvature of the grating, not on the Rowland circle.

6. Wadsworth mount. Wadsworth was the first to point out that if a concave grating is illuminated with parallel light, a stigmatic image is obtained on the grating axis (Wadsworth, 1895). The scarcity of fluorite prevents the use of large lenses achromatic in the ultra-violet; Fabry and Buisson (1910) therefore used a concave mirror with a slit in its focal plane to illuminate the grating with parallel light, though the source is then at the opposite end of the instrument to the plate-holder. This is inconvenient in an industrial laboratory, where the routine must provide for the examination of a large number of alloys.

Light, from a source whose image is focused on the slit S, falls upon a concave mirror M, which sends a parallel beam of light to the grating G (Fig. 17.5). The slit and grating are so close together that the aberration due to the mirror is small, and the grating spectra are focused on the plate Z without appreciable astigmatism. This permits the use of a Hartmann diaphragm at the slit, to produce juxtaposed comparison spectra.

Away from the grating normal horizontal and vertical foci no longer coincide. Equation (17.12) shows that when the object distance is infinite, the distance u'_V of the vertical image from the grating is

$$u'_V = \frac{R\cos^2 I'}{\cos I + \cos I'} \tag{17.16}$$

while the horizontal image distance u'_H is calculated in the next chapter (equ. 18.39) and shown to be

$$u'_H = \frac{R}{\cos I + \cos I' - \sec I} \tag{17.17}$$

so that the horizontal image lies outside the vertical.

In 1914 Meggers and Burns (1922) built a Wadsworth mount at the Bureau of Standards, and reported that careful tests revealed two foci, the focus for horizontal lines being 2 mm. further from the grating than that for vertical lines. The former is used to obtain the narrowest slit images, and the latter to secure sharpest definition along the length of the line.

The distance from the plate to the grating is $R/(1+\cos I)$, where R is the radius of curvature of the grating. (Equation 17.15.) This is the polar equation of a parabola, so that if the lines are to be sharp across the whole plate, some method must be devised for bending the plate. A curve could be built, but a varying curvature is not easily provided, so Meggers and Burns content themselves with a flat plate 20 cm. long, parallel to the face of the grating, and mounted on a steel beam; this beam pivots on a vertical axis through the face of the grating, the various positions being calibrated for spectral region and camera focus. In theory this set-up will yield only one line on the plate as sharp as possible, but in practice all lines are in satisfactory focus except those near the ends of the plate.

Meggers and Burns use a grating of radius 640 cm., ruled with 7500 lines per inch, so that the grating space is 3.387μ. With it they photograph spectra from 2000 A in the first order, where $I=5°$, to about 6000 A in the fourth order, where $I=45°$. The distance from the plate to the grating increases from 320.8 cm. in the first position to 374.9 cm. in the last. The dispersion is about 95μ/A. In measuring wavelengths use is made of a correction curve, obtained by plotting the difference between the actual wavelengths of standard lines, and those computed on the assumption that the spectrum is normal.

Compared with the Rowland mount the Wadsworth has several advantages besides its stigmatic image; it occupies about one-fourth the space, so that it is more easily made rigid, can be used in a smaller laboratory, and is less troubled by temperature gradients. With all this to gain, the makers of some industrial spectrographs have adopted the Wadsworth mount (Jarrell, 1942; Forrest and Straat, 1942).

Compa[illegible] with the Eagle mount, the only advantage of the Wadsworth mount is its stigmatic image, and against this must be set several disadvantages (Dieke, 1939). The Wadsworth mount requires more space, is less rigid, and more expensive; while as the focal curve is not a circle, but a parabola, the adjustment is more complex and must be carried out with greater care. No automatic adjustment appears to have been designed.

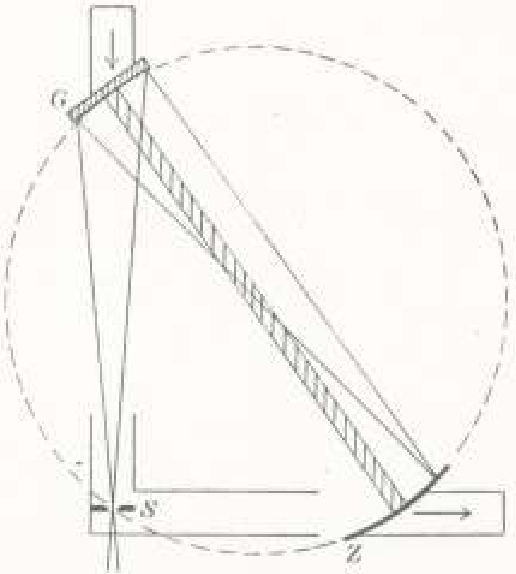

Fig. 17.6.—Rowland mount. The grating G and the plate Z move along two rails set at right angles to one another, while the slit S is stationary at their intersection.

As the mount brings the spectrum nearer to the grating, the dispersion is less than in a Rowland circle mount, though the resolving power remains unchanged. The intensity of the spectra is theoretically quadrupled, as the aperture ratio is doubled; this is rather misleading, however, as the Wadsworth mount should properly be compared not with another mount of the same grating, but another mount of a grating of half the focal length, so that the two instruments have the same dispersion. The Wadsworth image will then be more intense only because the Rowland circle is astigmatic, for some light is lost in reflection at the mirror.

7. Rowland and Abney mounts. In both these mounts the grating and plate-holder are fixed parallel to one another at opposite ends of a bar; this bar is a diameter of the Rowland circle. The mounts differ in that Rowland allowed the bar to move, while the source remained stationary (Fig. 17.6), whereas Abney (1886) kept the bar fixed and moved the source, whenever he wished to change from one spectral region to another (Fig. 17.7). Moving the source has commonly been considered a disadvantage so serious, that the Abney mount is now very seldom used.

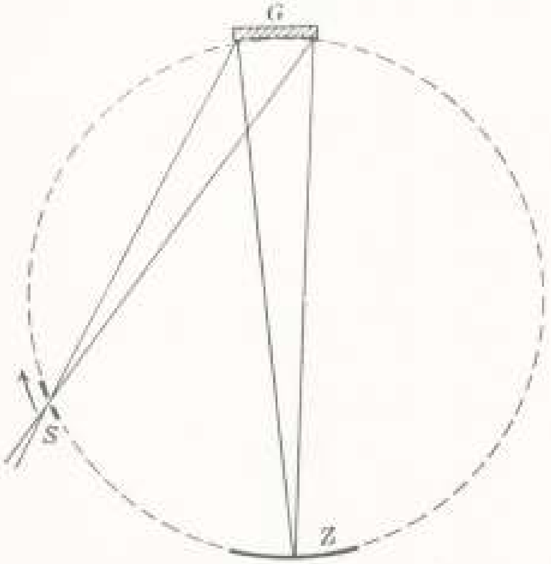

Fig. 17.7.—Abney mount. The plate *Z* is permanently fixed at the centre of curvature of the grating; to vary the wavelength the source must be moved round the Rowland circle.

In the Rowland mount the bar carrying the grating and plate-holder is supported on two carriages, which move along two ways fixed at right angles to one another, the entrance slit being at the intersection of the ways. In theory this is all that can be desired; in practice, carriages have never been made so rigid that the instrument will remain in accurate adjustment, when the spectral region is changed. The re-focusing is so troublesome that the Rowland mount is also obsolete.

In both mounts the spectrum is always normal, for we know that in general

$$m\lambda = b(\sin I + \sin I')$$

and if I is fixed we may differentiate and obtain

$$m\delta\lambda = b\cos I'\ \delta I'. \qquad (17.19)$$

When I' is small, as it is in this mounting, $\cos I' = 1$, and the change of wavelength is proportional to the distance along the plate. This property

was considered a great advantage, when grating spectrographs were used to measure wavelengths with all possible accuracy, but now that standard wavelengths are measured with a Fabry-Perot etalon, the normality of the spectrum hardly matters.

The astigmatism of both mounts is very large (Dieke, 1933), though of all mounts they are the easiest to correct, for the change of astigmatism across the plate is small, so that a correction made at the centre of the plate will usually be valid with sufficient accuracy over its whole length.

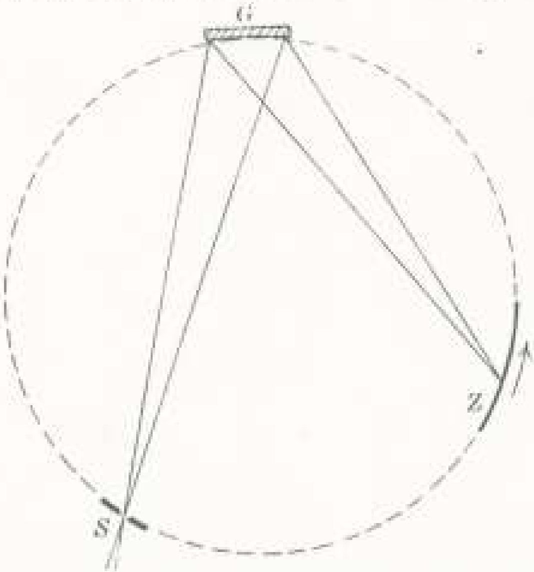

Fig. 17.8.—Paschen mount. The slit is fixed; the wavelength is altered by moving the plate round the Rowland circle.

This ease of correction makes the Abney mount attractive in an industrial spectrograph, which is to be used almost always in the same spectral region, for the source will then have to be moved but seldom. If, however, the astigmatism is to be corrected only in one region, as for instance in the range 2500 to 3500 A, which is most used in the spectrochemical analysis of alloys, just as good a correction can be obtained in a modified Eagle mount with the slit placed on the long wavelength side of the plate.

8. Paschen mount. In the Paschen mount (Runge and Paschen, 1902) the grating and slit are firmly mounted on concrete pillars; their position determines a Rowland circle, which is thus accurately located once for all, so that thereafter a plate-holder need only be placed on the circle to obtain a spectrum (Fig. 17.8). This facilitates a very rigid